A GapWaveguide-Fed Wideband Patch Antenna Array for 60-GHz Applications

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A Gap Waveguide-Fed Wideband Patch Antenna Array for 60-GHz Applications

Davoud Zarifi, Ali Farahbakhsh and Ashraf Uz Zaman

***Abstract*—This communication presents a wideband aperture-coupled patch antenna array based on Ridge Gap Waveguide (RGW) feed layer for 60-GHz applications. The novelty of this antenna lies in the combination of relatively new gap waveguide technology along with conventional patch antenna arrays allowing to achieve a wideband patch antenna array with high gain and high radiation efficiency. An 8×8-element array antenna is designed, fabricated and tested. Experimental results show that the bandwidth of VSWR <2.0 is up to 15.5% (57.5–67.2 GHz). More than 75% efficiency and higher than 21.5 dBi gain are achieved over the operational bandwidth. The results are valuable for the design and evaluation of wideband planar antenna arrays at millimeter-wave frequencies.**

***Index Terms*—Patch antenna, planar arrays, gap waveguide technology.**

I. Introduction

In recent years, there has been an increase in the development of millimeter-wave wireless communication systems at 60 GHz band due to the demand of high-data-rate short-range wireless communication [1]. The main challenge of the 60 GHz band is very high radio wave absorption caused by the resonance of oxygen molecules. One candidate as a solving method is using high gain antennas with high radiation efficiency.

Development of high-gain wideband millimeter-wave antenna arrays with high radiation efficiency has attracted increasing attention in the recent years. Different planar antenna arrays, such as microstrip and substrate-integrated waveguide (SIW) arrays and slot antenna arrays are the two main technologies for millimeter-wave applications [2-6]. The low efficiency of the large microstrip and SIW antenna arrays brings a lot of restrictions to their practical millimeter wave applications. One major aspect restricting the achievable gain of these antenna arrays is the losses in feeding networks. In fact, realizing a high-gain array antenna in the millimeter-wave band requires a low-loss feeding network. As common candidates, corporate-feed waveguide slot arrays have been used to achieve high gain and efficiency. At high frequencies, these antennas require accurate, high precision and expensive manufacturing [7]. Recently, the gap waveguide technology has been introduced and used in [8-10]. In this technology, the waveguide can be realized without any requirement of metal contact between the upper metal surface and the lower surface. This simplifies the mechanical assembly of the designed antennas and hence reduces the production cost for the antennas. To date, some wideband high gain and efficiency array antennas have been realized based on gap waveguide technology in different frequency ranges [11-17]. Also, the gap technology can be used for RF packaging which makes it possible to integrate the RF electronics with the gap waveguide antennas [18-19].

In this communication, aperture-coupled microstrip antenna arrays fed by ridge gap waveguide (RGW) feed networks are investigated at 60-GHz band. An Array of 64 radiating elements is designed and simulated. The main advantage compared to other reported gap waveguide based planar arrays is that this structure can keep a two layer planar profile compared with three layers slot arrays included feed network, cavity layer and radiating slots layer [12, 13]. Also, the dimensions of the proposed 2×2-element sub-array are 4.9 mm ($0.98\lambda_0$) × 4.9mm ($0.98\lambda_0$) which are smaller than 8.8 mm ($1.76\ \lambda_0$) × 8.8mm ($1.76\lambda_0$) [13] allowing limited range of scanning if needed. The simulation and measurement results show that the proposed array has high gain and efficiency for 60 GHz applications. The metal feed network can be easily manufactured by Computer Numerical Control (CNC) milling, moulding or by electric discharge machining.

The communication is organized as follows. Section II deals with the design of 2×2-element sub-array, feeding network, 8×8-element antenna array and the transition from RGW to WR-15. The performances of the antenna array are discussed in Section III and the simulation and measurement results are presented. Finally, Section IV provides a conclusion.

II. Antenna Design And Analysis

This section describes the design procedure and the simulation results of the antenna sub-array and complete array. The simulations are performed using the full-wave electromagnetic simulator CST MWS.

A. 2×2-Element Sub-array

The configuration of 2×2-element sub-array is depicted in Fig. 1. It consists of a dielectric layer, a patch layer and a RGW feed layer. Patches are metallic rectangles of 1.6 mm × 1.25 mm on a Duroid 6002 substrate (ε_r = 2.94, loss tangent = 0.0012 and thickness = 0.254 mm.). Two copper layers are on the opposite sides of the substrate with the thickness of the metal layers 18μm. The center to center spacing between adjacent patch elements is 2.45 mm ($0.49\ \lambda_0$ at 60 GHz) in both *x* and *y* directions. Thus, the problems associated with grating lobes will be much smaller than for the other gap waveguide slot array antennas [12, 13].

The microstrip patch is a narrow band resonant structure. There are many available techniques to enhance the bandwidth of microstrip patch antennas. Here, to expand the bandwidth, a coupling slot is used to feed center feed line of patches. Aperture coupled feed provides a greater radiation pattern symmetry and greater ease of design for larger impedance band width owing to a large number of design parameters. A wideband 2×2 patch antenna with SIW based aperture coupled feed has been proposed in [20] for W-band applications from 91-97 GHz (6.4% bandwidth). In our case, we use the topology of microstrip T-junctions to divide power with microstrip T-junctions to divide power with wideband characteristic. Thus a wider range of impedance matching is

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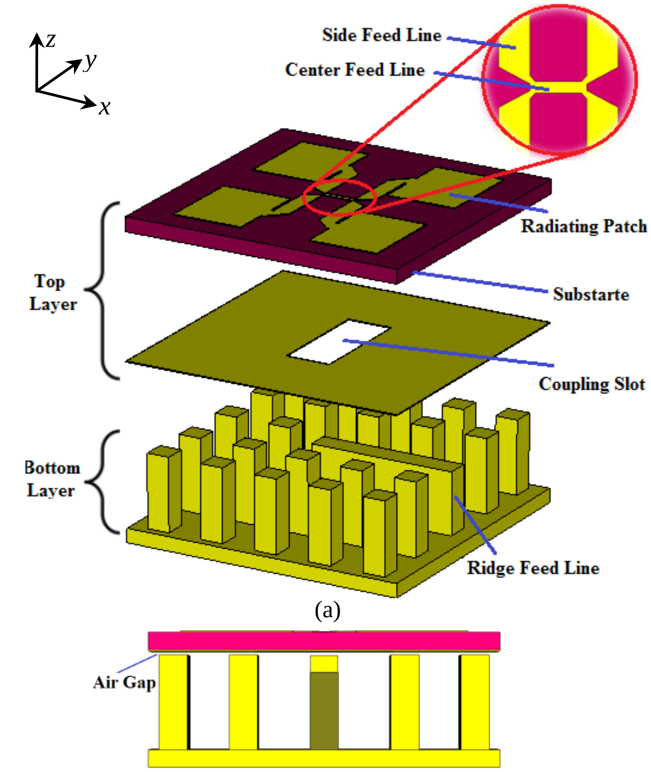

Fig. 1. 2×2-element sub-array. (a) Exploded view. (b) Side view.

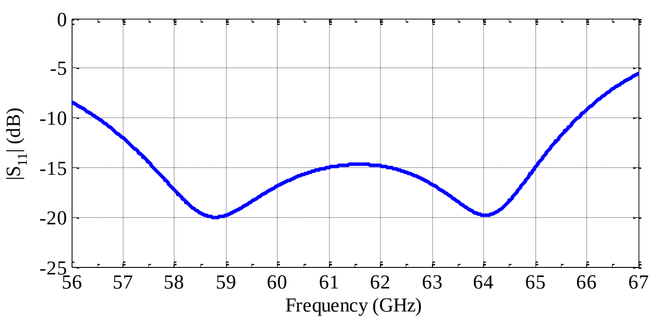

Fig. 2. Simulated reflection coefficient of proposed 2×2-element sub-array

achieved by proper design of the length and width of the aperture and width of center line feed.

The lower layer contains some metal pins and a ridge forming a RGW distribution network. Periodic metal pins are planted on both sides of the ridge to produce desired stop-band characteristics and to prevent wave propagation in unwanted directions. Based on [12, 13], the dimensions of pins are chosen to achieve a cut-off bandwidth from 40 to 100 GHz. As shown in Fig. 1(b) there is a small air gap between the top surface of pins and conducting plane so there is no requirement for electrical contact between them. The RGW feed structure excites the coupling slot etched in the ground plane of the substrate. By optimizing the dimensions of coupling slots and microstrip feed lines, four patches can be excited with same amplitude and phase [20]. This is performed by using optimization in CST to achieve acceptable matching and radiation properties. Notice that four radiating patches have the same phases and amplitudes of the E-field, which shows the sub-array has a maximum in the broadside.

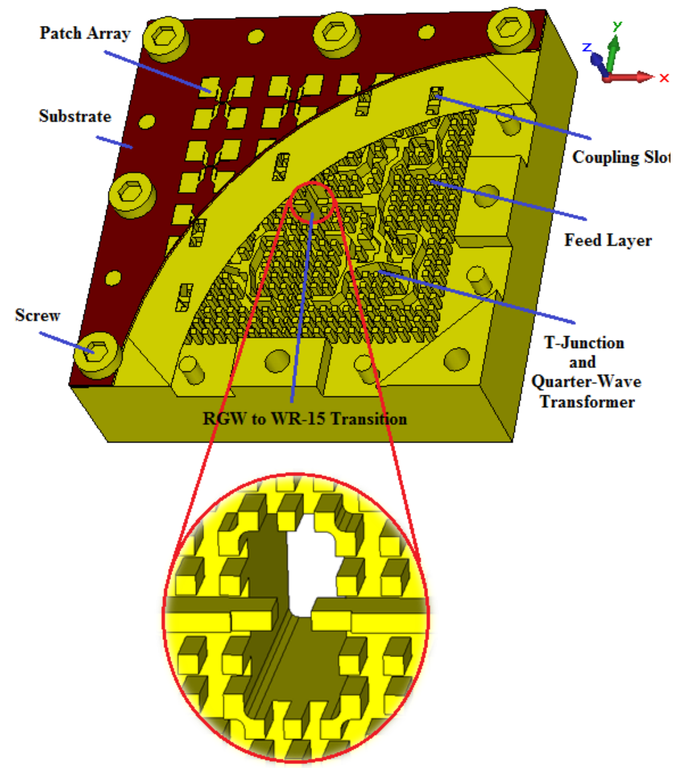

Fig. 3.Perspective view of 8×8-element patch antenna array.

The designed sub-array has 4.9×4.9 mm^2 dimensions in *x*- and *y* directions. The mutual coupling between sub-arrays is automatically included by using the infinite array approach. As shown in Fig. 2, the simulated reflection coefficient of the sub-array shows the bandwidth of 56.5-66 GHz (15.5%)for $|S11| <-10$ dB.

For high gain applications, an array with 8×8-patch antenna array is designed as shown in Fig. 3.The corporate feed network is realized by interconnecting T-junction power dividers. In lower layer, a RGW power divider is designed to feed upper 64 radiating patches uniformly by 16 rectangular coupling slots. The feeding network is based on the quarter-wave impedance transformers and matched T-junctions. The detailed design of different power dividers based on RGW technology has been discussed in [13].

For the purpose of measurement, a wideband and compact transition between WR-15 and RWG is designed, as shown in Fig. 3. Observe that at the end of the ridges, two steps are used, which makes the mode of RGW transform to the TE_{10} mode of rectangular waveguide. The transition is designed and optimized for minimum reflection and insertion loss in the operating frequency band.

Notice that due to the differential outputs provided by the transition in two ridges, left hand side and right side of the feed layer are mirrored. The input power to rectangular waveguide excites the antenna by the designed transition and then flows through a RGW 16-way power divider. For achieving the desired matching, all the parameters of the transition, power divider and microstrip structure are optimized. The detailed optimal dimensions of the proposed antenna array are given in Table I.

TABLE I. DESIGN PARAMETERS OF 8×8-ELEMENT ARRAY

Component	Parameter	Value (mm)
Radiating Patches	Length	1.6
	Width	1.25
	Center to center space	2.45
	Width of side feed lines	0.3
	Width of center feed line	0.1
	Larger Length of T- Junction	0.35
	Smaller Length of T- Junction	0.06
Pins	Dimensions	0.4×0.4×1.3
Ridge	Height	1.1
	Width	0.4
T-Junctions	Larger Length	3
	Smaller Length	0.3
Quarter-wave Transformers	Length	0.65
	Width	0.93
Air Gap	height	0.05
Coupling Slots	Length	2
	Width	0.8
RGW to WR-15 Transition	Length of Step	0.8
	Height of Step	0.14

III. SIMULATION AND EXPERIMENTAL RESULTS

To verify the simulated results, a prototype of the designed patch antenna array was fabricated by standard CNC milling techniques, which is exhibited in Fig. 4.To verify the antenna operation experimentally, the antenna was fed by a standard rectangular waveguide. Measurements on S_{11}, gain, and radiation patterns were performed by a millimeter-wave band vector Network Analyzer in an outdoor test range measurement system.

The simulated and measured input reflection coefficients of the antenna array are shown in Fig. 5. The measured bandwidth for $|S11| < -10$ dB is 15.5% from 57.5 to 67.2 GHz. The differences between the measured and the simulated results are because of the tolerances of manufacturing and assembling tolerances.

Fig. 6 shows the frequency behavior of the simulated directivity and measured gain, as well as the aperture efficiency. However, there is less than 1 dB difference between the measured gain and simulated directivity results. This discrepancy results partially from deviation of the dielectric and metallic losses in simulation and the measurement setup and also the tolerance of the fabricated antenna. Still the total radiation efficiency of the antenna array is higher than 75% over the operating frequency band. The difference between simulated and measured values 60-61 GHz is due to measurement uncertainty which is considered to be ±0.25 dB or approximately 0.5dB using standard gain horn in out measurement chamber.

Fig. 7 shows the simulated and measured normalized radiation patterns at 58 and 62 and 67 GHz in both E- and H-planes. The main reason of the small difference is measurement uncertainty. The measured radiation patterns

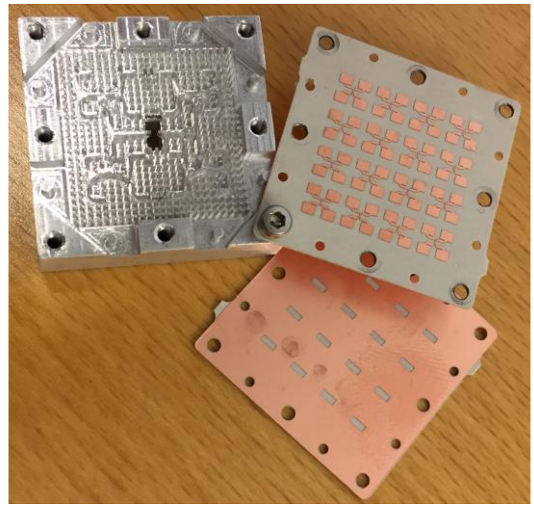

Fig. 4. Photograph of fabricated antenna. The structure has dimension of 28×28×7 mm^3.

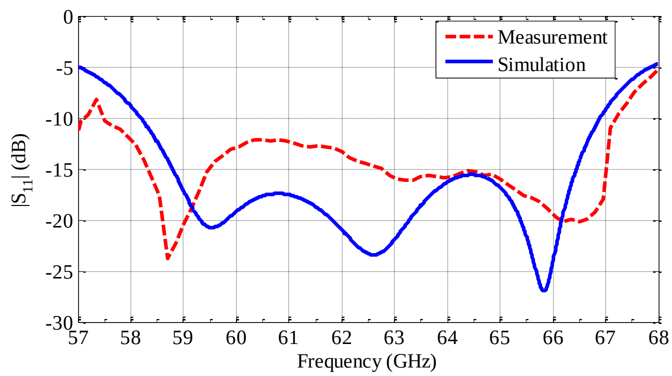

Fig. 5.Simulated and measured $|S_{11}|$ of 8×8-element patch antenna array.

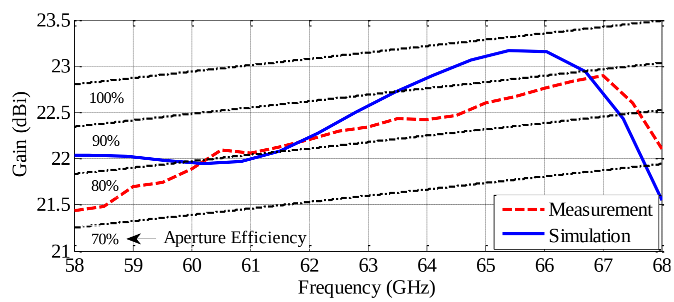

Fig. 6. Simulated directivity and measured gain of 8×8-element array antenna and 100%, 90%, 80% and 70% efficiency lines.

with 3-dB beamwidth at 62 GHz are around 13° and 15° in E- and H-planes, respectively. Also, the measured maximum sidelobe level at 62 GHz is -13.5 dB and the front-to-back ratio is better than 25 dB. In addition, the measured cross-polarization level of the antenna is detected as –28 dB at the boresight.

In Table II, we compare our work with different published 60-GHz antenna arrays and we summarize the findings in terms of bandwidth, realized gain and efficiency (gain/ $D_{uniform}$). Observe that the efficiency of our RGW fed patch antenna array is higher than those of the proposed arrays in [2-

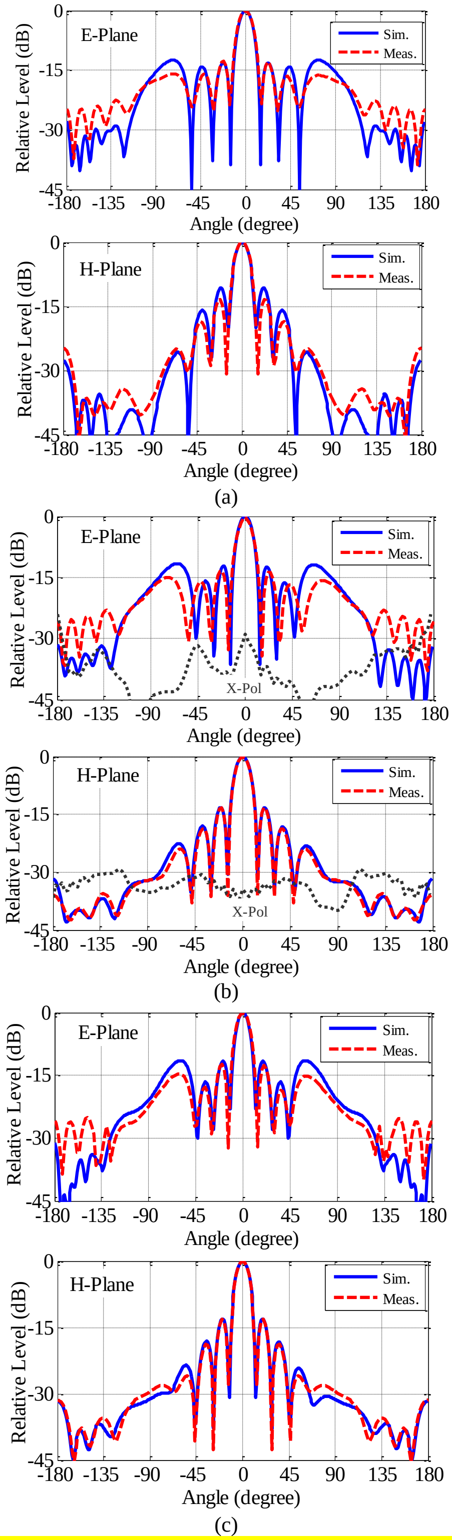

Fig. 7. Simulated and measured radiation patterns of the 8×8-element array. (a) 58 GHz, (b) 62 GHz, (c) 67 GHz.

5]. This is mainly due to the absence of the dielectric loss in the feeding network of antenna array. In addition, the proposed antenna array can keep a two layer planar profile compared with other three layers RGW slot arrays [12, 13].

TABLE II. COMPARISON BETWEEN PROPOSED AND REPORTED 60-GHZ PLANAR ANTENNA ARRAYS

	Our work	[12]	[2]	[3]	[4]	[5]
Aperture Size (mm^2)	19.6×19.6	32×32	20×15	35×34	47×31	35×31
Number of Elements	64	256	16	64	64	64
Frequency (GHz)	57.5-67.2	56.2-65	55-68	56.3-65.7	54.7-65.1	57.5-67
Bandwidth(%) $\|S11\|$ <−10 dB	15.5	14	21	15.4	17	14.1
Gain (dBi)	21.5-23	24.7-26	12.8-15.6	21.2-24.2	20-22.1	< 26
Efficiency (%)	75-87	60-80	58-70	40-42	44.5	60-68.5
Technology	Gap Waveguide	Gap Waveguide	Microstrip	SIW-LTCC	SIW-LTCC	SIW
Number of Layers	2	3	1	2	3	3

IV. CONCLUSIONS

An 8×8-element patch array antenna fed by RGW was proposed in this communication. The simulation results have been verified by measuring a fabricated prototype of the proposed antenna array. Experimental results showed satisfactory agreement with the simulation. At the operation frequency (57.5-67.2 GHz), the fabricated prototype has an impedance bandwidth of 15.5% for a reflection coefficient lower than -10 dB, a gain of higher than 21.5 dBi, and a sidelobe level below -13 dB in both E- and H-planes. The proposed antenna array fed by RGW could be utilized in a wide range of applications where microstrip antennas are usually used.

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